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RESEARCH ARTICLE

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Typical off-design analytical performances of internal combustion engine cogeneration

Abstract Based on experimental data, typical off-design characteristic curves with corresponding formulas of internal combustion engine (ICE) are summarized and investigated. In combination with analytical solution of single-pressure heat recovery steam generator (HRSG) and influence of ambient pressure on combined heat and power (CHP) system, off-design operation regularities of ICE cogeneration are analyzed. The approach temperature difference ΔT_a , relative steam production and superheated steam temperature decrease with the decrease in engine load. The total energy efficiency, equivalent exergy efficiency and economic exergy efficiency first increase and then decrease. Therefore, there exists an optimum value, corresponding to ICE best efficiency operating condition. It is worth emphasizing that ΔT_a is likely to be negative in low load condition with high design steam parameter and low ICE design exhaust gas temperature. Compared with single shaft gas turbine cogeneration, ΔT_a in ICE cogeneration is more likely to be negative. The main reason for this is that the gas turbine has an increased exhaust gas flow with the decrease in load; while ICE is on the contrary. Moreover, ICE power output and efficiency decrease with the decrease in ambient pressure. Hence, approach temperature difference, relative steam production and superheated steam temperature decrease rapidly while the cogeneration efficiencies decrease slightly. It is necessary to consider the influence of ambient conditions, especially the optimization of ICE performances at different places, on cogeneration performances.

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Keywords internal combustion engine (ICE), cogeneration, heat recovery steam generator (HRSG), off-design, superheated steam, saturated steam, ambient pressure

1 Introduction

Internal combustion engine (ICE) and heat recovery steam generator (HRSG) are the most important power components in distributed energy system. They often run under off-design conditions due to changes in load or ambient conditions or both. Therefore, part load analysis is even more important than that of design point performance, and it has more practical value.

Currently, various numerical methods and computer codes have been proposed. Most of the simulations involve many structure parameters and experimental data. It is necessary to have typical off-design analytical performances owing to convenient calculation and summary. Besides, performance of ICE is sensitive to ambient conditions. So, attention should be paid to engine power output and efficiency as well as off-design performances of cogeneration.

For the above mentioned reasons, typical off-design characteristic of ICE cogeneration is studied, regarding ICE specific power output as independent variable, mainly focusing on the off-design performance of ICE cogeneration for the saturated steam system and the superheated steam system. Meanwhile, ICE performance variations and its cogeneration caused by the ambient pressure are introduced.

2 ICE CHP system

The typical ICE cogeneration schematic diagram is shown in Fig. 1. When fuel burns in an engine cylinder, the shaft work is converted into power by a generator. The residual

energy is discharged through the exhaust system, the cooling system, the lubrication system, and radiation, etc. Large amount of high-grade heat, whose temperature is about 400°C–600°C, is discharged into the atmosphere. But this heat can be recovered in a heat recovery steam generator to produce superheated steam, saturated steam or hot water. The heat taken away through the cooling system has a lower grade, whose outlet water temperature is about 80°C–100°C. The recovery heat is usually used for heating or as domestic hot water and so on.

According to the analysis above, the total recovery heat consists of the heat recovery from exhaust gas and that from cooling water. In order to make a comparison between the performances of single-shaft gas turbine and its cogeneration, only the heat taken away by the exhaust system is analyzed. That is to say, the heat taken away by the cooling system is released into the atmosphere.

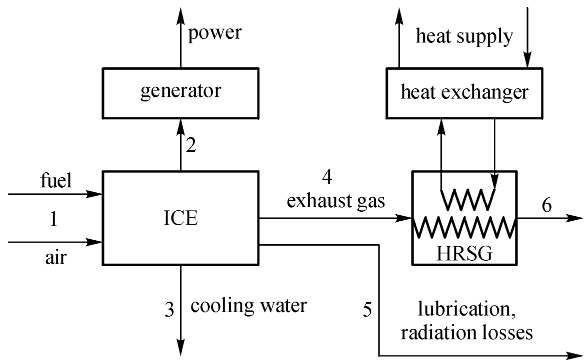


Fig. 1 Schematic diagram of ICE cogeneration

It can be found that the variation of HRSG performance is caused by two factors which are ICE exhaust gas temperature T_4 and exhaust gas flow G_4. ICE often runs under off-design conditions owing to engine load and ambient pressure. As a result, T_4 and G_4 change. Part-load performances of cogeneration are derived based on typical analytical component—ICE and HRSG—performances.

2.1 Typical off-design performances of ICE

There are mainly two kinds of ICEs—diesel engine and gas engine—in a cogeneration. The engine exhaust gas temperature and efficiency have great differences due to the diversity of engine types, cylinder numbers, fuel types, and cooling methods, etc. To obtain universal regularities of ICE performances, a group of off-design formulae are fitted owing to many experimental data which are obtained from various engine types [1,2]. It should be pointed out that the regularities summarized in this way may not suit a specific case exactly, but they do represent the general and typical performances of a kind of ICE set. Typical part-load performances of cogeneration are obtained by these representative typical formulae.

In this paper, most parameters are represented by the ratios to their design values. The relative variation of ICE exhaust gas temperature, exhaust gas flow and generation efficiency versus power output can almost be summarized as a single curve that is consistent with the practical data respectively, as shown in Fig. 2; the fitting formulae are:

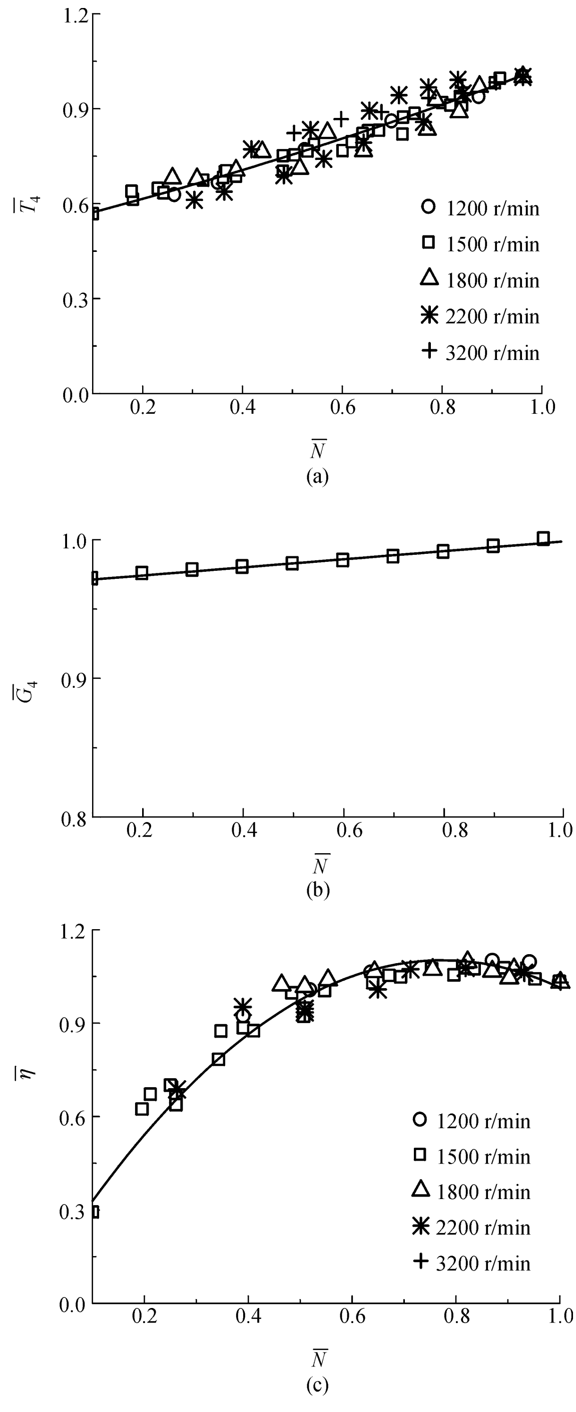


Fig. 2 Relative variation of ICE exhaust gas temperature, exhaust gas flow and generation efficiency versus power output
(a) Relative exhaust gas temperature variation; (b) relative exhaust gas flow variation; (c) relative efficiency variation

$$\overline{T}_4 = T_4/T_{40} = 0.53 + 0.38\overline{N} + 0.09\overline{N}^2, \tag{1}$$

$$\overline{G}_4 = G_4/G_{40} = 0.968 + 0.029\overline{N}, \tag{2}$$

$$\overline{\eta} = \eta/\eta_0 = 0.13 + 2.47\overline{N} - 1.6\overline{N}^2. \tag{3}$$

The standard differences of Eqs. (1)–(3) are 3.29%, 0.13% and 4.1% respectively, which confirms that these fitting formulae are proven to be typical enough to represent the performances of the present ICE set. Generally, ICE for generation has a constant operating speed due to the fixed power frequency. Nowadays, the frequency for power network in China is 50 Hz, thus the operating speed of the engine can only be set at 3000 r/min, 1500 r/min, 1000 r/min and 750 r/min etc. [3]. Off-design performance of ICE is the changing law of engine performance with a constant operating speed.

The variation of relative exhaust gas temperature $\overline{T}_4$ and relative exhaust gas flow $\overline{G}_4$ under off-design operation is shown in Figs. 2(a) and (b) respectively. Both of them drop in part load while the former decreases more quickly. The variation of efficiency $\overline{\eta}$ is shown in Fig. 2(c). As the load decreases, the engine efficiency first increases and then decreases. There exists a maximum value which corresponds to the engine's lowest fuel consumption.

2.2 Typical off-design performance of HRSG

As an important waste heat recovery equipment in cogeneration, HRSG can be classified into superheated steam HRSG, saturated steam HRSG and hot water HRSG based on the outlet working fluid [4]. Superheated steam HRSG is composed of a superheater, an evaporator and an economizer, while saturated steam HRSG consists of an evaporator and an economizer. ICE cogeneration is suitable for single-pressure HRSG owing to the low exhaust gas flow and low power output. In this paper, typical off-design performances of saturated and superheated steam HRSG are analyzed.

There are many calculation methods for off-design performances of HRSG, one of which is analytical solution. Analytical solution is the simplest and most effective means for thermal system analysis and numerical solution check. When exhaust gas temperature T_4 and exhaust gas flow G_4 are independent variables, analytical expressions of saturated steam HRSG are listed as follows [5]:

$$\Delta T_{\mathrm{p}} = (T_4 - T_{\mathrm{p}}) / \sqrt[\overline{G}_4]{b_1}, \tag{4}$$

$$\Delta T_{\mathrm{a}} = (-d + \sqrt{d^2 - 4c})/2, \tag{5}$$

$$T_6 = T_{\mathrm{p}} + \Delta T_{\mathrm{p}} - (T_4 - T_{\mathrm{p}} - \Delta T_{\mathrm{p}}) \times (T_{\mathrm{p}} - \Delta T_{\mathrm{a}} - T_{\mathrm{wi}}) / (\Delta T_{\mathrm{a}} + \overline{L}), \tag{6}$$

$$\overline{G}_s = \overline{G}_4 (T_4 - T_{\mathrm{p}} - \Delta T_{\mathrm{p}}) / \left[b_2 (\overline{L} + \Delta T_{\mathrm{a}}) \right]. \tag{7}$$

Off-design analytical expressions for superheated steam HRSG, which are proposed in Ref. [6], are listed as follows:

$$T_{\mathrm{g1}} = X + T_{\mathrm{p}} - c_2/3c_1, \tag{8}$$

$$\Delta T_{\mathrm{p}} = (T_{\mathrm{g1}} - T_{\mathrm{p}}) / \sqrt[\overline{G}_4]{b_1}, \tag{9}$$

$$T_{\mathrm{se}} = \left(1 + b_6 \overline{G}_4\right) T_{\mathrm{g1}} - \left(b_6 \overline{G}_4 - 1\right) T_4 - T_{\mathrm{p}}, \tag{10}$$

$$\overline{G}_{\mathrm{s}} = b_5 \overline{G}_4 (T_4 - T_{\mathrm{g1}}) / (T_{\mathrm{se}} - T_{\mathrm{p}}), \tag{11}$$

$$\Delta T_{\mathrm{a}} = \overline{G}_4 (T_{\mathrm{g1}} - T_{\mathrm{p}} - \Delta T_{\mathrm{p}}) / \overline{G}_{\mathrm{s}} b_2 - \overline{L}, \tag{12}$$

$$T_6 = T_{\mathrm{p}} + \Delta T_{\mathrm{p}} - \overline{G}_{\mathrm{s}} b_3 (T_{\mathrm{p}} - \Delta T_{\mathrm{a}} - T_{\mathrm{wi}}) / \overline{G}_4. \tag{13}$$

In Eq. (8), X is a real root of $X^3 + pX + q = 0$, where

$$p = \frac{c_3}{c_1} - \frac{c_2^2}{3c_1^2},$$

$$q = \frac{c_4}{c_1} - \frac{c_2 c_3}{3c_1^2} + \frac{2c_2^3}{27c_1^3},$$

$$\overline{L} = L/C_{\mathrm{pw}}.$$

The relevant coefficients b_1, b_2, b_3, b_5, b_6, c_1, c_2, c_3, c and d are proposed in Refs. [5,6], whose definitions are given in the nomenclature.

T_4, G_4 and η are functions of the engine power output respectively, which is shown in Eqs. (1)–(3). When the specific power output is the independent variable, the typical off-design analytical solutions of HRSG can be obtained by substituting Eqs. (1)–(3) into Eqs. (4)–(12). Besides, expressions of ICE cogeneration evaluation criteria such as power/heat ratio, total energy efficiency, equivalent exergy efficiency and economic exergy efficiency can be obtained in combination with the engine exhaust gas output parameters in Refs. [3,7]:

$$r = w/H, \tag{14}$$

$$Z = (w + H)/Q, \tag{15}$$

$$\eta_{\mathrm{e}} = [w + AH]/Q, \tag{16}$$

$$\theta = [w + BH]/Q, \tag{17}$$

where coefficients A is the ratio of heat exergy to heat energy ($A = 0.128$) while B is the price ratio of heat to power ($B = 0.305$) proposed in Ref. [7].

3 Typical off-design performances of ICE cogeneration with saturated steam

Typical off-design performances of ICE cogeneration are shown in Figs. 3–6. The design parameters are: C_{pw0}= 4.187 kJ/(kg·K), T_{40}= 773 K, P_{s0}= 0.5 MPa, T_{wi0}= 378 K, ΔT_{p0}= 20 K, and ΔT_{a0}= 20 K.

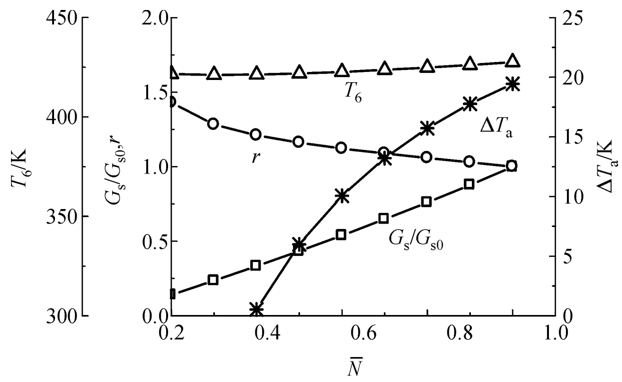


Fig. 3 Analytical off-design performance of saturated steam cogeneration

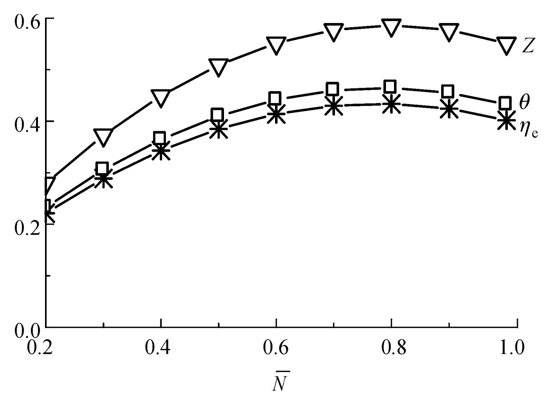


Fig. 4 Off-design performance of efficiency

Typical variations of cogeneration exhaust gas temperature T_6, relative steam production G_s/G_{s0}, approach temperature difference ΔT_a and power/heat ratio r are described in Fig. 3. T_6 is almost not influenced in part load; power/heat ratio increases slowly; while relative steam production and approach temperature difference drop fast in part load. As lower engine load results in lower engine exhaust gas temperature and exhaust gas flow rate, HRSG cannot provide enough heat for steam production with a low engine load, which is required for supplemental combustion and other technologies. Approach temperature difference is likely to be negative in low load performance, where water in the economizer will be evaporated. So, dry-burning HRSG is considered.

The power and heat are regarded as the same for total energy efficiency. On the contrary, equivalent exergy efficiency and economic exergy efficiency are considered as the grade and economy differences of heat and power respectively [3,7]. The variations of cogeneration efficiencies are shown in Fig. 4. It can be found that the heat grade and economy are far below the power. Cogeneration efficiencies first increase and then decrease with the decrease of part load. There exists an optimum value corresponding to ICE best operating condition.

According to the analysis above, approach temperature difference of HRSG is likely to be negative when the engine load is 0.4, which is of considerable importance to the safe running of the economizer in HRSG. However, this problem can be solved by dry-burning HRSG with increasing equipment cost or by avoiding operating in low load. The approach temperature difference variation of ICE cogeneration is different from that of single-shaft gas turbine CHP system [8]. One reason for this is that the engine exhaust gas flow rate drops in part load, as shown in Fig. 2 (b). The other reason may be that ICE exhaust gas temperature drops faster than that of gas turbine. On the contrary, the exhaust gas flow increases in gas turbine part load condition.

Moreover, off-design analytical solutions of HRSG in Ref. [6] are only suitable when approach temperature difference is not less than 0, so are the thermal curves in Figs. 5–11.

Both ICE design exhaust gas temperature T_{40} and steam parameter P_{s0} have significant influences on off-design performances of cogeneration, as shown in Figs. 5 and 6.

The influences of ICE design value of exhaust temperature on approach temperature difference, steam production, power/heat ratio, and efficiency are shown in Fig. 5. The design exhaust gas temperature is set at 723 K, 773 K, 823 K and 862 K. Totally, the design exhaust gas temperature has no significant influence on economic exergy efficiency and equivalent exergy efficiency. Approach temperature difference is likely to be 0 as T_{40} decreases. Hence, the normal operating range for the combined system becomes narrow. Meanwhile, the system recoverable heat, steam production and total energy efficiency decline, but power/heat ratio increases as engine exhaust gas temperature declines a lot.

The influence of design steam parameter P_{s0} on off-design performances of cogeneration is shown in Fig. 6. It seems that P_{s0} has a significant influence on approach temperature difference. A minor increase of steam pressure will lead to a faster drop of approach temperature difference along with engine load decrease, which is dangerous for HRSG. When high steam pressure is adopted, the possibility of a negative approach temperature differences under off-design operation is worthy of more attention. The variation of steam pressure has little influence on system steam production, efficiency and power/heat ratio.

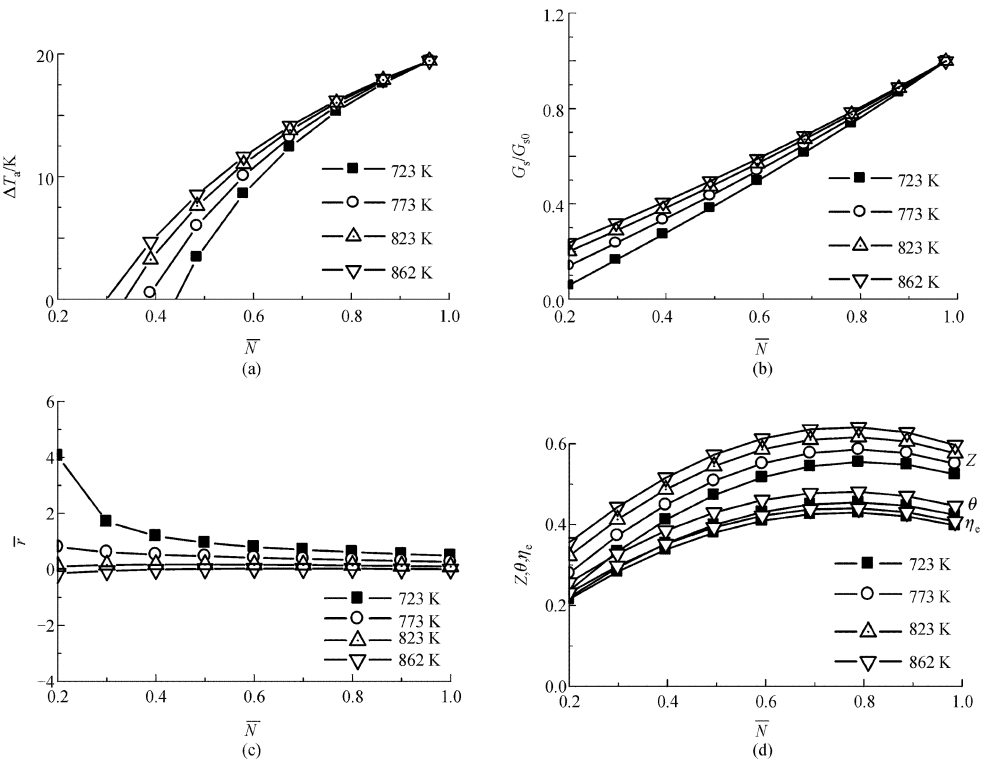


Fig. 5 Influences of ICE design value of exhaust temperature
(a) Approach temperature difference; (b) steam production; (c) power/heat ratio; (d) efficiency

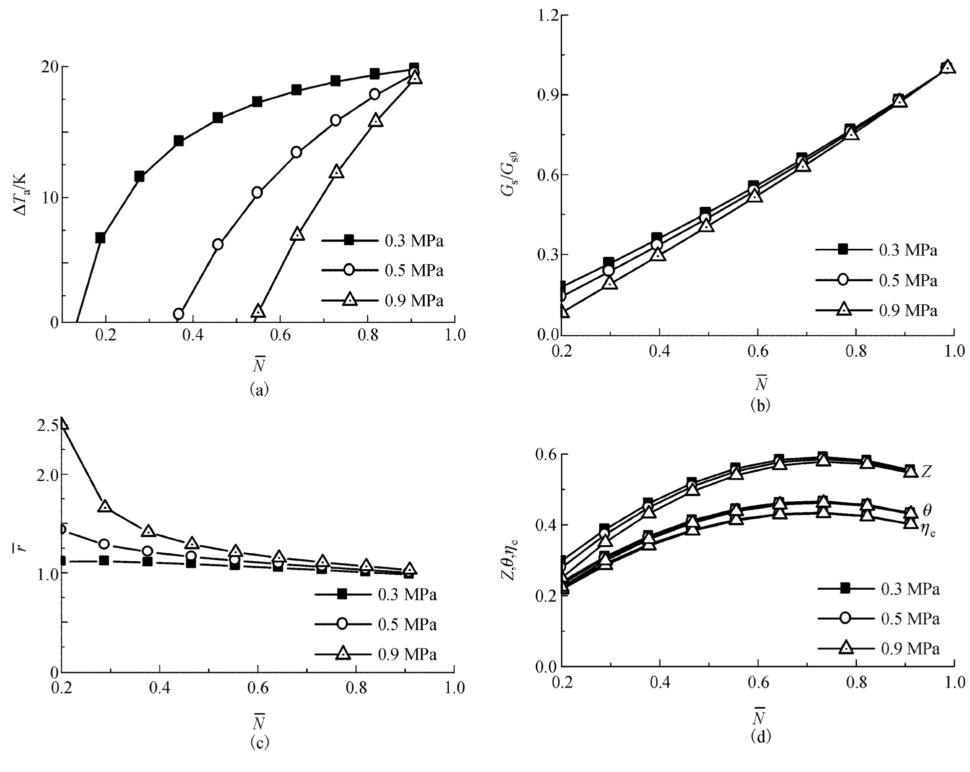


Fig. 6 Influence of design steam parameter P_{s0} on the off-design performances of cogeneration
(a) Approach temperature difference; (b) steam production; (c) power/heat ratio; (d) efficiency

4 Typical off-design performances of ICE cogeneration with superheated steam

Typical off-design performances of ICE cogeneration for superheated steam are shown in Figs. 7 and 8. The related design parameters are the same as those of saturated steam system for convenience of comparison except superheated steam temperature T_{se0}, which is set at 633 K.

Compared with saturated system, superheated steam cogeneration has an additional thermal parameter —superheated steam temperature T_{se}, which declines fast as engine load declines. Exhaust gas temperature of the cogeneration, relative steam production and power/heat ratio have similar variation law with saturated steam system. Approach temperature difference in Fig. 7 is likely to be negative when the engine load is less than 0.4, which is lower than that of saturated system. The variations of total energy efficiency, equivalent exergy efficiency and economic exergy efficiency under off-design operation are shown in Fig. 8. Due to higher heat recovery, these efficiencies are a little higher than those of the saturated system.

Both ICE design exhaust gas temperature T_{40} and steam parameter P_{s0} have significant influences on off-design performances of cogeneration for superheated steam, as shown in Figs. 9 and 10. The design value of exhaust gas temperature is set at 723 K, 773 K and 823 K. According to the analysis, relative steam production, power/heat ratio, total energy efficiency, equivalent exergy efficiency and economic exergy efficiency have little difference from those of a saturated system. For simplicity, emphasis will be put on approach temperature difference and superheated steam temperature owing to their importance.

The total amount of heat recovery of the cogeneration declines with the decrease of exhaust gas temperature and part load. As a result, steam production and superheated

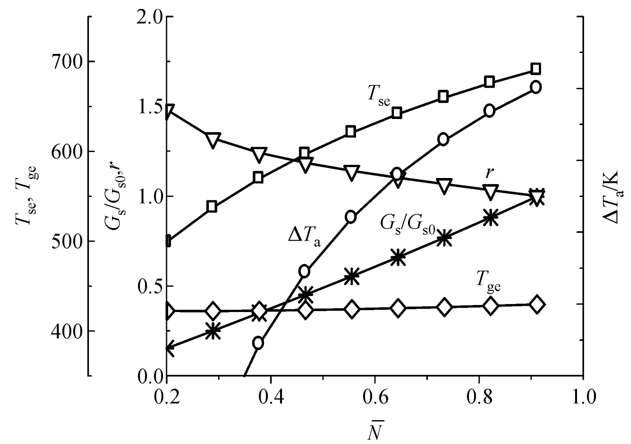


Fig. 7 Typical off-design performance of superheated steam system

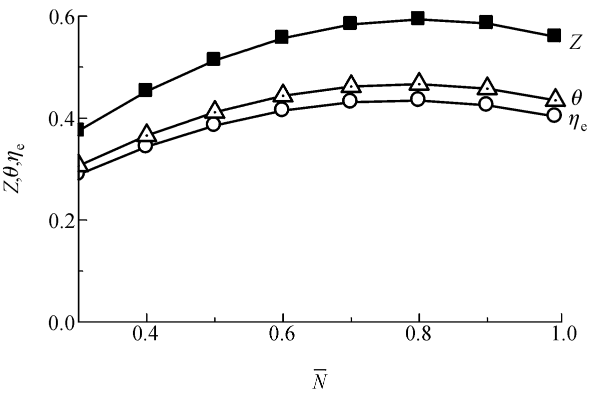


Fig. 8 Off-design performance of efficiency

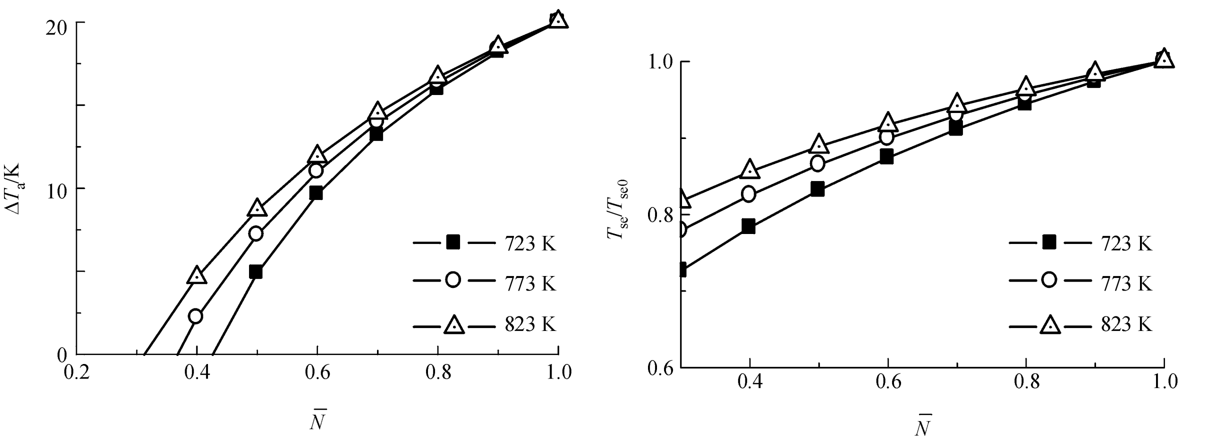


Fig. 9 Influence of T_{40} on approach temperature difference and superheated steam temperature
(a) Approach temperature difference; (b) superheated steam temperature

steam temperature declines. Approach temperature difference becomes 0 with appropriate load of 0.4, which has little difference from that of saturated system. As a result, the water in the economizer will evaporate when $\Delta T_a \leqslant 0$, which affects the safety operation of HRSG.

The influence of different steam pressure (0.3 MPa, 0.5 MPa, 0.9 MPa) on approach temperature difference and superheated steam temperature is shown in Fig. 10. The quality of superheated steam is higher with higher steam pressure; hence, approach temperature difference is likely to be negative and the safety operation of HRSG should be a great concern. HRSG cannot run under total operating mode with a steam parameter of 0.3 MPa. Similar to a saturated system, superheated system has a poorer off-design performance than gas turbine cogeneration. Besides, the design steam pressure almost has no influence on superheated steam temperature.

5 Influence of ambient condition on cogeneration performances

Three important ambient factors, i.e., ambient pressure, temperature and humidity, affect engine performances. In this paper, emphasis is put on ambient pressure owing to its significant influence on the performance of ICE cogeneration.

Based on the experimental data in Refs. [9,10], the variation of engine main performances under ambient pressure is shown in Fig. 11(a). $\overline{N}-P_0$ and $\overline{\eta}-P_0$ are approximately linear functions. ICE efficiency and power output decline with low ambient pressure. And ambient pressure has comparably even more influence on power output.

Excess air ratio is a basic factor used to characterize mixture concentration and the degree of combustion reaction. Air density declines as ambient pressure declines, which will lead to low air quantity inhaled into the cylinder. The fuel quantity supplied to the diesel engine declines with constant excess air ratio. Hence, engine effective power output decreases, which will lead to the decrease of thermal efficiency and ICE exhaust gas temperature.

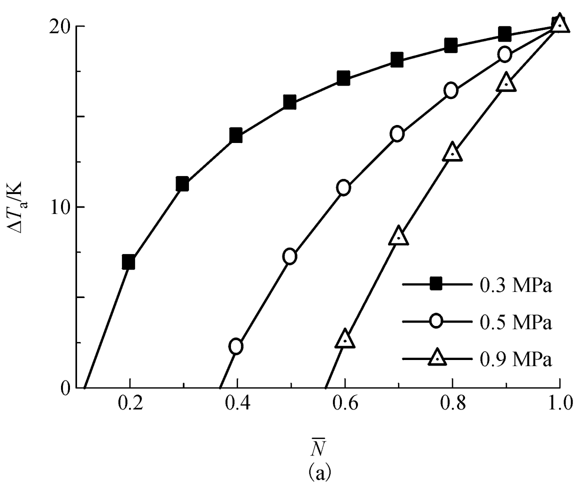
The influence of ambient pressure on cogeneration performances and efficiencies is shown in Figs. 11(b) and (c). The relative steam production, superheated steam temperature and approach temperature difference decrease rapidly when ambient pressure decreases, which should be considered seriously in practical works. Not only should the safe operation of the HRSG be considered when ambient pressure decreases, but also the thermal energy output of the cogeneration with a large decrease in steam production. The cogeneration exhaust gas temperature is slightly affected by ambient pressure; power/heat ratio, total energy efficiency, equivalent exergy efficiency and economic exergy efficiency decline slightly.

6 Conclusions

Based on experimental data, typical off-design performance of ICE is summarized and concluded. Combining analytical off-design performance of single pressure HRSG with saturated/superheated steam and influences of ambient pressure, typical off-design performances of ICE cogeneration are derived as follows:

1) ICE exhaust gas temperature and exhaust gas flow drop as load drops. The efficiency first increases and then decreases. There exists an optimum value.

2) The variation of engine load has little effect on cogeneration exhaust gas temperature. However, approach temperature difference, relative steam production and



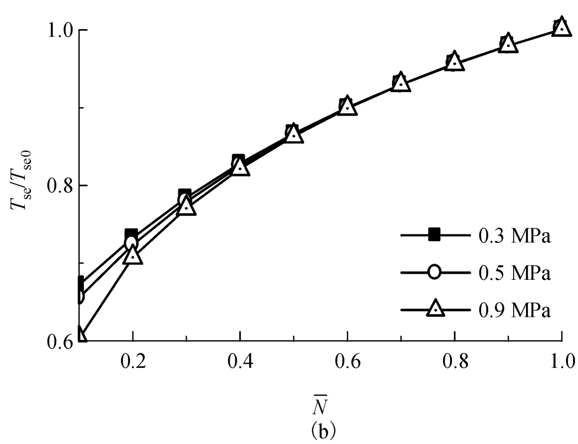


Fig. 10 Influence of different steam pressure P_{s0} on approach temperature difference and superheated steam temperature
(a) Approach temperature difference; (b) superheated steam temperature

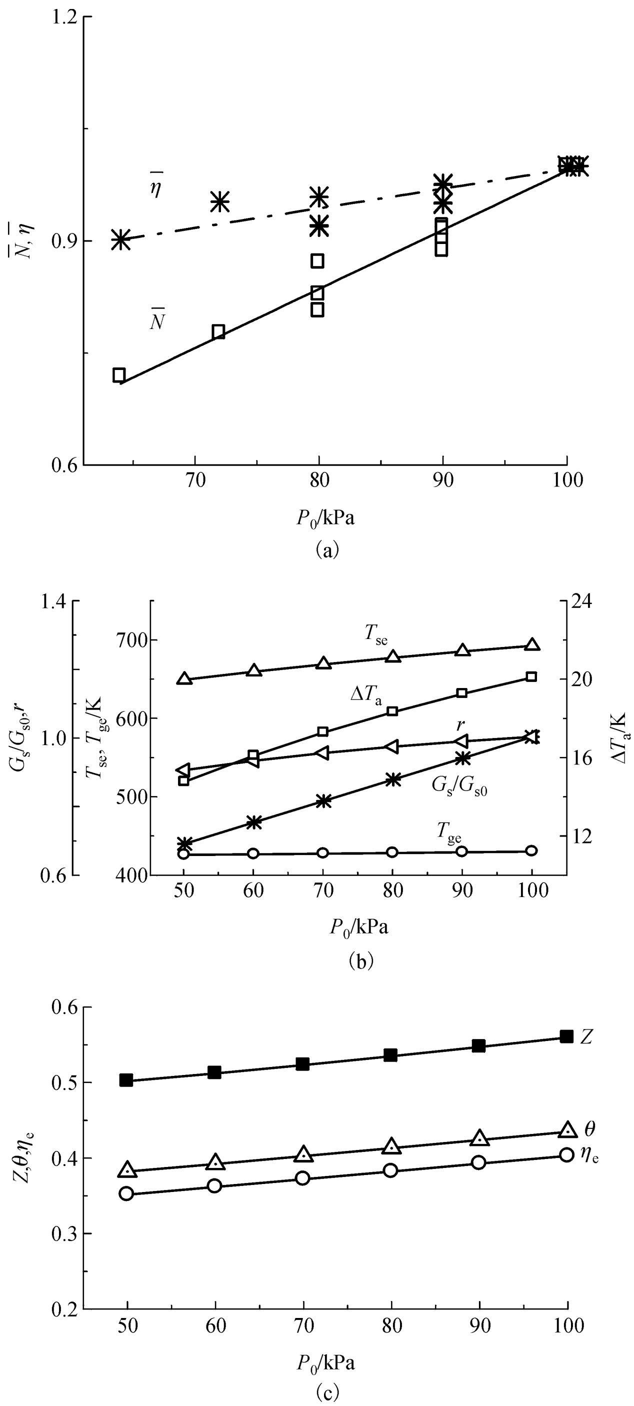


Fig. 11 Variation of engine main performances under ambient pressure
(a) ICE performance; (b) cogeneration performance; (c) cogeneration efficiency

superheated steam temperature decrease rapidly. The total energy efficiency and equivalent/economic exergy efficiency first increase and then decrease. There exists a maximum value.

3) The variation of design ICE exhaust gas temperature has little influence on the performances of saturated cogeneration, so does it on superheated cogeneration. Approach temperature difference ΔT_a, total energy efficiency and superheated steam temperature decrease while power/heat ratio increases as design exhaust gas temperature decreases. The design steam parameter has a significant influence on approach temperature difference. A minor increase will lead to a faster drop of ΔT_a along with engine load decrease.

4) Both ICE power output and its efficiency decrease as ambient pressure decreases, while power output decreases even more rapidly. Relative steam production, approach temperature difference and efficiencies decrease as ambient pressure decreases, which should be considered in practical condition.

5) Compared with gas turbine cogeneration, approach temperature difference in ICE cogeneration is likely to be negative. The main reason for this is that single shaft gas turbine has an increasing exhaust gas flow with the decrease in load and the decrease in exhaust gas temperature.

6) The influence of off-design performances of cogeneration has little difference between saturated steam cogeneration and superheated steam cogeneration.

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Notation

A	ratio of heat exergy to heat energy
B	price ratio of heat to power
C_{pw}	specific heat at constant pressure of the feed water
G	mass flow rate
H	recycled heat value
L	latent heat of vaporization
N	power output
P	pressure
Q	fuel heat value
r	power/heat ratio
T	temperature
T_p	saturated steam temperature
T_{se}	superheated steam temperature
w	work
Z	total energy efficiency
ΔT_a	approach temperature difference
ΔT_p	pinch-point temperature difference
η	efficiency
η_e	equivalent exergy efficiency
θ	economic exergy efficiency
Superscript	
$\bar{}$	divided by design value
Subscripts	
i	inlet parameter
e	outlet parameter
s	steam
w	feed water
0	design value
4*	ICE exhaust gas
6*	HRSG exhaust gas

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